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(71) Applicant (for all designated States except US): TELIA AB [SE/SE]; S-123 86 Farsta (SE).

(72) Inventors; and
(75) Inventors/Applicants (for US only): ISAKSSON, Mikael [SE/SE]; Borgmästarevägen 7, S-973 42 Luleå (SE). ENGSTRÖM, Bo [SE/SE]; Blidvägen 189, S-951 37 Luleå (SE).

(74) Agent: KARLSSON, Berne; Telia Research AB, Rudsjörterrassen 2, S-136 80 Haninge (SE).

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(54) Title: METHOD AND APPARATUS FOR SYNCHRONIZATION IN DIGITAL TRANSMISSION SYSTEMS OF THE OFDM TYPE

(57) Abstract

The invention relates to a method and apparatus for synchronization of transmitters and receivers in digital transmission systems of the OFDM type. The system uses FFT technique to carry out the modulation and demodulation procedures. According to the invention, the transmitter sends synchronization frames with known frequencies and phase positions and with known time intervals in certain time slots. The receiver carries out a series of time-shifted FFT operations over the time position where the synchronization frame is calculated to be. For each operation, a cross-correlation is carried out in the frequency plane of the output signal with the known frequency function of the synchronization frame. The correlation maximum is detected, and this determines the time slot which contains the synchronization frame, whereupon this is used as time base for the following data frames.

TITLE OF THE INVENTION: METHOD AND APPARATUS FOR
Synchronization IN DIGITAL TRANSMISSION SYSTEMS OF THE
5   OFDM TYPE

FIELD OF THE INVENTION

The present invention relates to a method and apparatus
to determine synchronization parameters for time shift,
phase turning and frequency drift in a broad-band digital
10   transmission system of the OFDM type (Orthogonal
Frequency Division Multiplexing). The technique which is
used is that certain time slots have known
synchronization frames containing tones or subcarriers in
the whole frequency spectrum with known phase selected in
15   accordance with a pseudo-random pattern (PRBS-sequences).

The receiver carries out a series of time-shifted FFT
operations over the time position where the
synchronization frame is calculated to be. For each FFT
operation a cross-correlation is carried out in the
20   frequency plane of the output signal with the known
frequency function of the synchronization frame. The
cross-correlation means that a very well-defined
correlation maximum is only obtained when the FFT
operation is carried out in exactly the correct time
25   slot. The phase for the cross-correlation maximum shows
clearly on the synchronization frame phase and is used
for phase correction during demodulation of data. The
frequency deviation which is used when regulating this
can be calculated from the cross-correlation. The
30   frequency error is obtained by reading off the position
of the cross-correlation maximum in the correlation
sequence.

The apparatus is provided with RAM memory, FFT processors and digital signal processors (DSP).

STATE OF THE ART

It is already known to use correlation calculations between a known and a received sequence in the frequency plane.

US-A-4 577 334 shows a receiver for digital data modulated on a carrier wave signal. At the beginning of a data transmission, a training sequence with a known frequency is transmitted. The receiver contains circuits for determining certain parameters such as the phase between the transmitted training sequence and a corresponding sequence generated in the receiver. The receiver uses a DFT (Discrete Fourier Transform) filter to determine the correlation between the input signal and a locally generated frequency.

US-A-4 754 449 describes a receiver which, using a Fourier transformer, receives a number of FDMA channels and transforms these into a single TDM channel. Any phase error in the incoming information is detected by allowing a symbol window to sweep forwards and backwards over the incoming symbols. An error signal is generated if a time shift is detected for an individual symbol compared to previous transmissions.

US-A-4 701 939 relates to a method and equipment for obtaining synchronization between a transmitter and a receiver. Synchronization sequences are transmitted in the form of pseudo-random patterns. The received synchronization sequences are compared by an auto-correlation technique with known sequences, and in this way synchronization between the transmitter and receiver can be obtained.

US-A-5 148 451 concerns a device for synchronizing a

mobile unit with an incoming carrier wave. The incoming
carrier wave is modulated with data and a unique
sequence. This unique sequence is periodically
incorporated in the data information in each frame. The
5   unique sequence is also stored locally in the mobile
units. A circuit performs a cross-correlation between the
modulated unique sequence and the stored sequence. The
result of the cross-correlation is used for frame and
carrier wave synchronization.

10   It is, however, not known to perform time-shifted FFT
operations and cross-correlate the result in the
frequency plane and to use such synchronization methods
in OFDM networks.

BRIEF DESCRIPTION OF THE DIAGRAMS

15   The invention will now be described in detail with
reference to the attached diagrams, of which
Fig. 1 is a block diagram of the transmitter and the
receiver in an OFDM system,
Fig. 2 shows the insertion of synchronization frames in
20   accordance with the present invention,
Fig. 3 shows a diagram of the detection of a
synchronization frame, and
Fig. 4 is a block diagram of the synchronization part in
the receiver in accordance with the present invention.

25   DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In order to make it easier to understand the invention we
will first present a brief general description of the
modulation method OFDM and its characteristics.

By OFDM is meant Orthogonal Frequency Division Multi-
30   plexing. The basic idea of OFDM modulation is that the
data to be transmitted is divided up into a large number
(N) of modulated subcarriers so that each of the sub-
carriers is given a low bit speed. The reason for this is

to counteract the effects of frequency-selective fading
which causes inter-symbol interference. By using a large
number of frequency-divided channels where each one has
a symbol time which is considerably longer than the
5   length of the channel's time dispersion, the effect of
this problem is reduced. In frequency-selective fading,
different parts of the frequency spectrum are damped
greatly in different ways, resulting in dips in the
frequency band. For OFDM-modulation this means that
10   certain subcarrier channels can be completely or partly
extinguished, which means that the information from these
is lost. This information can be regained by channel
coding. The modulation method using combined OFDM and
channel coding is usually called COFDM (Coded OFDM).

15   What distinguishes conventional frequency-division
modulation from OFDM is that the frequency spectrum of
the adjacent subcarriers overlaps, which gives an optimal
frequency utilization. This can be carried out by the
signals having orthogonal characteristics which make it
20   possible to modulate each channel so that the
neighbouring channels are not disturbed. An attractive
feature of this is that the modulation and demodulation
processes can be carried out using FFT technique (Fast
Fourier Transform).

25   Fig. 1 shows a block diagram of the transmitter and the
receiver in an OFDM system. Inverse FFT is carried out in
the transmitter on a block of N symbols. The symbols
before the IFFT operation can be regarded as frequency
functions for each subcarrier and can be given any
30   modulation form. The time function of the symbols is
transmitted over the channel, and FFT of this is carried
out in the receiver before demodulation of the data.

The present invention provides a method for synchronizing
OFDM systems of the above type. The method is based on
35   inserting known synchronization frames in time. The
synchronization frames frame a number N of data frames

which form a block, as shown in Fig. 2.

The purpose of the synchronization frames is to make it possible, via digital signal processing in the receiver, to estimate a time reference for sampling of data. In addition the signal processing permits the estimation of the phase turning the channel has given the synchronization frame and an estimate of the frequency drift. These parameters are then used in the detection of subsequent data frames. The concept is based on assuming that the channel is approximately stationary (time invariant) between the synchronization frames so that the parameters estimated can be used in the detection of subsequent data frames. The synchronization frames are repeated at known intervals which are selected based on the channel's rate of change, ie the rate the parameters vary, and on the calculation capacity which is required to estimate the synchronization parameters.

The synchronization frame is designed for processing in the frequency plane through FFT technique and cross-correlation. It is of the utmost importance that the whole frequency spectrum is used in order to give robustness against frequency-selective fading.

The frame consists of known frequencies with known phase positions. The frequencies are divided by number and frequency separation in such a way that during the FFT operation in the receiver the same number of samples are taken as the number of points in the FFT. The frequencies are selected with such separation that they lie exactly in frequency for each point in the FFT. The phase position for each frequency is selected in accordance with a PRBS pattern (Pseudo Random Binary Sequence) consisting of -1 and 1. For example, so-called M sequences can be used as PRBS sequence. The choice of PRBS sequences is to be based on the auto-correlation characteristics and is one of the cornerstones of the synchronization method.

The synchronization frame is generated by inverse FFT
(IFFT) in the transmitter. According to the invention the
synchronization frame is generated by generating fre-
quencies (tones) in the frequency plane with predeter-
5   mined phase, calculating IFFT, and transmitting the time
function of the operation in the time slots concerned
between the data frames. Since the synchronization frame
is known and repeated continuously, the IFFT operation
can be carried out in advance and stored in EPROM. This
10   stored time function of the synchronization frame can
thereby be transmitted by direct reading from EPROM in
the predetermined time slots.

The receiver has a measure on time position and phase for
the previous synchronization frame. On account of distor-
15   tion of the channel and shortcomings in the transmitter
and receiver, these parameters must be updated for each
new block of data frames. To update these parameters the
previous time position is used to find the new one by
carrying out a series of FFT operations.

20   As shown in Fig. 3, first more samples are taken than the
FFT length over the area where the synchronization frame
is calculated to be in time. A series of FFT operations
overlapping in time, sliding FFT, is carried out on these
samples, in order to find the position of the time slot
25   where the synchronization frame is situated.

After each FFT operation, cross-correlation is carried
out against the known frequency function of the
synchronization frame. Since the phase of the respective
frequency was selected as PRBS sequences, the cross-
30   correlation will give a very well-defined amplitude
maximum only in the time slot which contains the synchro-
nization frame. This cross-correlation maximum is
detected for each time shift of the signal, and at the
time shift where the greatest (only) maximum is obtained
35   this is used as the time base for the subsequent data.

The phase for the cross-correlation maximum shows clearly
the phase of the synchronization frame and is used for
phase compensation when detecting the subsequent data.

The cross-correlation also provides information on
5   frequency deviations. These deviations usually arise as
a result of deviations between the oscillators of the
transmitter and receiver, but can also arise as a result
of Doppler effects in mobile systems. The frequency error
appears by the amplitude maximum in the cross-
10   correlation varying around the midpoint in the sequence
(maximum in the midpoint - no frequency error). If the
amplitude maximum is moved one step in the sequence it
corresponds to a frequency drift on an FFT-point's
resolution frequency separation.

15   Another characteristic of the method is that the phase
deviation and amplitude for various frequencies in
different parts of the frequency spectrum can be read
off directly from the FFT for the synchronization
sequence which can be used for channel estimation in the
20   event of frequency-selective fading.

Fig. 4 shows a block diagram of the synchronization
component in the receiver in accordance with the present
invention.

The receiver consists of a sampling unit, direct memory
25   (RAM), FFT processors and digital signal processors
(DSP).

The sampling unit digitizes the signal by sampling and
buffers this in the RAM memory (complex signal). The RAM
memory acts as buffer for a sufficient quantity of data
30   of the signal so that the time reference for data
detection is able to be given as an address-offset to
this memory (circular buffer).

There are two FFT processors in the receiver. One FFT

processor is for detecting data and the other FFT
processor is for detecting synchronization parameters.
The result of the operation from the FFT processor used
for synchronization is read in by DSP units and
5   processed for estimating the synchronization parameters.

The parameter for time synchronization is given to the
address handler for the FFT processor for data detection
as an address-offset to the RAM memory, ie where this is
to begin to read in the data.

10   The estimated parameter for phase turning is given to the
demodulation unit after the FFT processor. This unit
demodulates each subcarrier channel and corrects phase
and amplitude.

The frequency drift which is measured is used by a
15   frequency regulating unit which is not part of the
invention. Frequency regulation can be carried out in
various ways. One way is to control numerically
controlled oscillators (NCO) by mixing and to feed back
the result to the regulator. Another way is to
20   compensate for the frequency drift digitally before the
FFT operation in the receiver with similar feed-back.

An FFT processor is a signal processor optimized for
vectorial operations on large data quantities, such as
FFT, correlation and FIR filtering. This type of
25   processor is considerably quicker than general signal
processors for these types of operation.

The FFT processor is adapted for carrying out the
operations in the frequency plane. By this is meant that
the architecture is optimized for carrying out FFT (Fast
30   Fourier Transform) on incoming data. After the FFT
operation, filtering and correlation, etc, can be carried
out in the frequency plane as vectorial multiplying by
the frequency function of the transmission function. The
FFT processor has a memory structure which is so

constructed that what is known as ping-pong technique can
be used. By this is meant that data is read from one RAM
memory, processed in the FFT processor and stored in the
second RAM memory. The parameters or coefficients which

5   are used for each operation are stored in a special RAM
memory.

In the synchronization method in accordance with the
invention the FFT processor is used for sliding
cross-correlation in the frequency plane against the

10   received synchronization frame. A general arrangement for
the operations for the FFT processor can be described by
the following pseudo code:

```
for j=(tau_old-k) to (tau_old+k) do
    f=FFT(s(j to j+fft_len-1))
15      c=corr(f_sync,f)
    save_to_DSP(c)
end
```

A correlation in the frequency plane can be carried out
by multiplying the data by the time function of the

20   synchronization frame in the time plane before the FFT
operation. This method is considerably more efficient
than carrying out the operation by a correction after
the FFT operation and is therefore used in this
invention. An advantage of this procedure is that the

25   FFT processor supports this operation, which it does not
do for a pure correction. The pseudo code can thereby be
modified for this synchronization method by:

```
for j=(tau_old-k) to (tau_old+k) do
    sm=conjugate(t_sync)*s(j to j+fft_len-1)
30      c=FFT(sm)
    save_to_DSP(c)
end
```

The operations which the FFT processor carries out are
then as follows in descriptive text:

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1. Read in the input signal sample from the previous time base tau_old. From tau_old-k to (tau_old+k-fft_len) the input signal sample is stored in the RAM memory. The factor k is selected dependent upon the maximal time shift which is calculated and upon how often this is updated. The calculating capacity which is available is also decisive.

2. For each time shift of the stored input signal, multiplication by the time function of the synchronization frame is carried out. This is stored in a bank in the coefficient RAM memory. After multiplication, FFT is carried out on the result, giving the cross-correlation in the frequency plane. The cross-correlation is stored for further processing by DSP.

3. When all operations above have been carried out for all time shifts of the signal and the new time base, tau_new, has been estimated, a further FFT operation is carried out for the new time base. This operation is carried out without frequency correlation and is to estimate the channel's distortion of the synchronization frame. This gives values for phase and amplitude distortion for the whole frequency spectrum, which permits compensation when demodulating data.

It is of the greatest importance to minimize the load on the DSP processor for broad-band signal processing since this is to the power ten slower than FFT processors in calculating capacity. However, a DSP processor has a considerably greater instruction set than a vector processor and can therefore perform operations which are more or less impossible with a vector processor. Examples of such operations are scalar operations such as comparisons, bit manipulation, memory operations and the ability to construct large complex program structures.

In accordance with the invention, the DSP processors have

the task of reading in the correlation sequences which are obtained from the FFT processor. From these correlation sequences, the DSP can find the correlation maximum and calculate its time base and phase turning.

5   The time base is used for controlling the sampling of data to the FFT processor for data demodulation. The phase turning is supplied to the demodulating unit after the FFT processor where phase compensation and correction take place.

10   After this, the frequency drift is estimated by processing the correlation sequence's selected time base. This parameter is used by the unit for frequency regulation.

The DSP also processes the channel estimate which is
15   obtained from the FFT operation for the correct time base and supplies this to the demodulation unit.

In this way the present invention provides a method and apparatus for synchronization of an OFDM system.

The invention has the following advantages compared with
20   previously known techniques:

- The synchronization is based on the whole frequency spectrum.

- The transmitter and receiver in an OFDM modem operate in the frequency domain. According to the invention, all
25   synchronization parameters in the frequency domain are estimated, which gives a similar hardware architecture to that for demodulation of data.

- OFDM modulation by FFT technique automatically gives a high level of controllability of discrete frequencies
30   and their phase position.

- The method gives a relatively high proportion of

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synchronization parameters from the same operations: time shift, phase turning, frequency drift and channel estimating.

5 - The method includes acquisition, ie finding the abovementioned initial parameters for the subsequent data, but provides a good basis for tracking (phase compensation, frequency regulation and channel correction during demodulation).

10 - An accurate estimate of frequency drift gives high potential for digital frequency regulation. By this is meant that if the limits of the frequency error are known, ie lie within a known interval, instead of regulation via analog components (numerically controlled oscillators, etc) regulation of the sampled signal can 15 be carried out digitally.

- Instead of inserting special synchronization frames, what are known as "guard spaces" in the data frames can be used as synchronization frames. This means that no degradation of transmission capacity is required for the 20 synchronization. However, during synchronization the synchronization frame must be sampled at the same rate as the data frame and a shorter FFT carried out (type 1/8 data FFT) on this, which gives a worse resolution in frequency and correlation. This has, however, the 25 advantage that the FFT operation is carried out much more quickly.

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PATENT CLAIMS

1. Method for synchronization of transmitter and receiver
in digital transmission systems of the OFDM type which
uses FFT technique to carry out the modulation and
5   demodulation process, characterized in that synchro-
nization frames with known frequencies and phase
positions are sent at known intervals by the transmitter,
in that a series of time-shifted FFT operations are
carried out by the receiver, in that the receiver carries
10   out cross-correlation against the known frequency
function after each FFT operation, in that the
correlation maximum is detected, which determines the
time slot which contains the synchronization frame,
whereupon this is used as time base for the subsequent
15   data frames.

2. Method according to Claim 1, characterized in that the
phase position   for the respective synchronization
frame's frequency is selected in accordance with a
random pattern (PRBS).

20   3. Method according to Claim 1 or 2, characterized in
that the respective synchronization frame is generated by
generating frequencies in the frequency plane with
predetermined phase, calculating the inverse Fourier
transform (IFFT) of this and transmitting the time
25   function of the operation in predetermined time slots
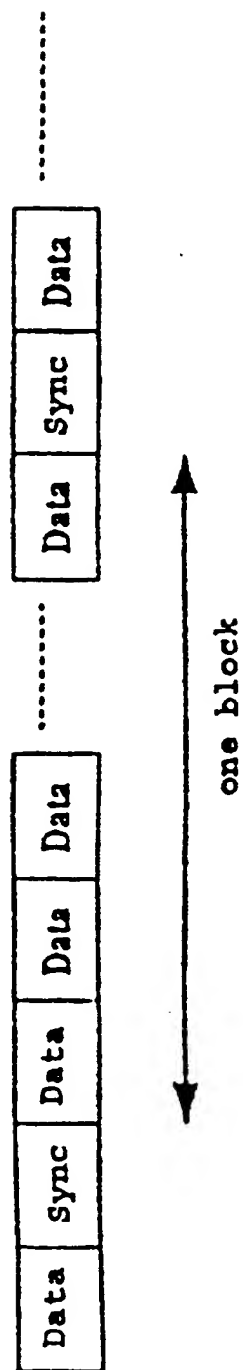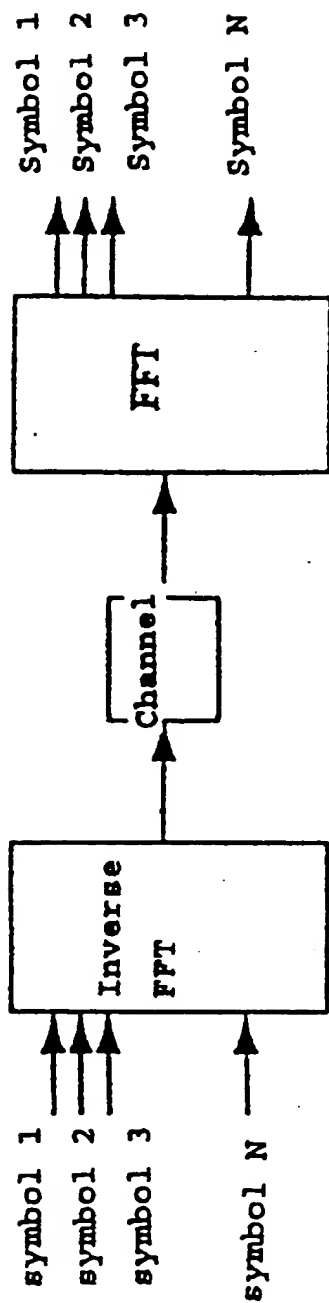between the data frames.

4. Method according to Claim 3, characterized in that the
IFFT operation is stored in advance in an EPROM, the
synchronization frame being able to be transmitted by
30   direct reading from the EPROM in the predetermined time
slots.

5. Method according to any of the preceding claims,
characterized in that the series of time-shifted FFT
operations is carried out by first sampling more samples

than the FFT length over the area where the
synchronization frame is calculated to be in time, and in
that a series of FFT operations overlapping in time is
carried out on the sample.

5   6. Apparatus for synchronization in digital transmission
       systems of the OFDM type which utilizes FFT technique to
       carry out the modulation and demodulation procedures in
       order to carry out the method upon receiving a signal in
       accordance with any of the preceding claims, charac-
10   terized by a sampling unit for digitization of the
       signal by sampling, direct memory (RAM) for storing a
       sufficient quantity of samples of the signal, an FFT
       processor for detection of data,   an FFT processor for
       detection of synchronization parameters by means of
15   cross-correlation in the frequency plane, a digital
       signal processor (DSP) for reading in correlation
       sequences and from these detecting the correlation
       maximum and calculating the required time base.

       7. Apparatus according to Claim 6, characterized in that
20   the FFT processors are signal processors optimized for
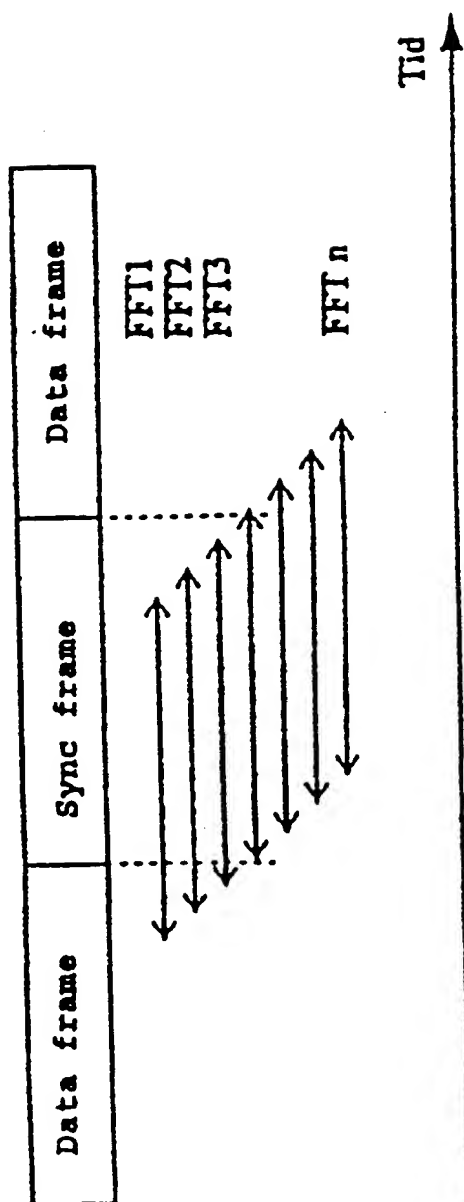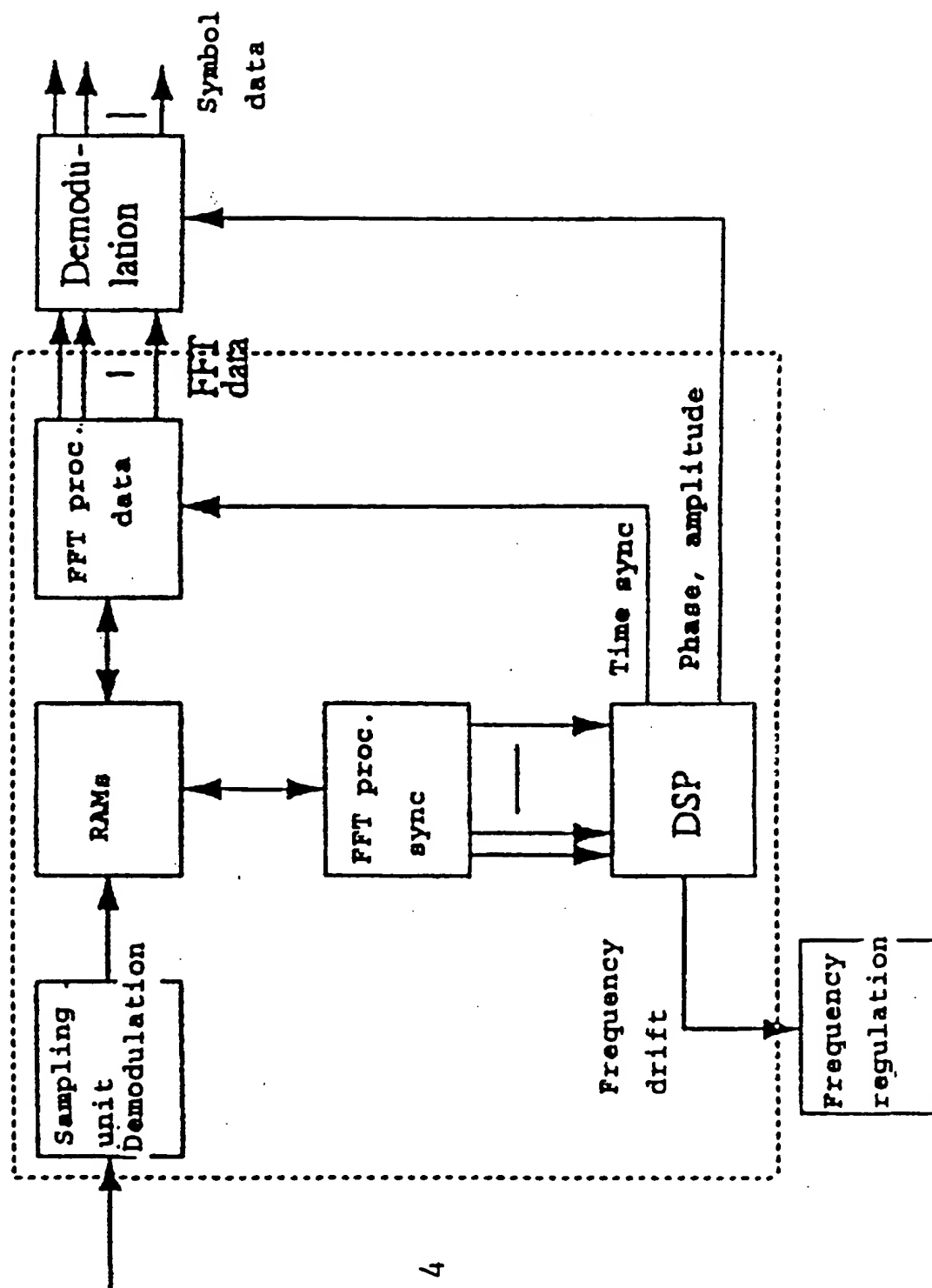   vectorial operations on large quantities of data.

FIG 1

FIG 2

Data frame	Sync frame	Data frame

FFT1
FFT2
FFT3

FFT n

Tid

FIG 3

FIG 4

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: H04L 5/06, H04L 7/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: H04L, H04J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CLAIMS, WPI, PAJ, EPODOC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,A	EP, A2, 0556807 (NEC CORPORATION), 25 August 1993 (25.08.93), see the whole document	1-7
A	US, A, 5148451 (SUSUMU OTANI ET AL.), 15 Sept 1992 (15.09.92), see the whole document	1-7
A	WO, A1, 9210043 (THOMSON-CSF), 11 June 1992 (11.06.92), abstract	1-7

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	
"E" erlier document but published on or after the international filing date	"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 November 1994	28 -11- 1994
Name and mailing address of the ISA/ Swedish Patent Office	Authorized officer

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